

# Observation of the first gravitational microlensing event in a sparse stellar field : the Tago event

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## ABSTRACT

We report the observation of the first gravitational microlensing event in a sparse stellar field, involving the brightest ( $V=11.4$  mag) and closest ( $\sim 1$  kpc) source star to date. This event was discovered by an amateur astronomer, A. Tago, on 2006 October 31 as a transient brightening, by  $\sim 4.5$  mag during a  $\sim 15$  day period, of a normal A-type star (GSC 3656-1328) in the Cassiopeia constellation. Analysis of both spectroscopic observations and the light curve indicates that this event was caused by gravitational microlensing rather than an intrinsically variable star. Discovery of this single event over a 30 year period is roughly consistent with the expected microlensing rate for the whole sky down to  $V = 12$  mag stars. However, the probability for finding events with such a high magnification ( $\sim 50$ ) is much smaller, by a factor  $\sim 1/50$ , which implies that

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the true event rate may be higher than expected. This discovery indicates the potential of all sky variability surveys, employing frequent sampling by telescopes with small apertures and wide fields of view, for finding such rare transient events, and using the observations to explore galactic disk structure and search for exoplanets.

*Subject headings:* Galaxy: disk – stars: individual (GSC 3656-1328) – gravitational lensing

## 1. Introduction

The idea that a star’s gravity magnifies the light from a perfectly aligned background source star, so-called gravitational microlensing, was first presented by Einstein (1936) and developed by Refsdal (1964). However, it was thought very difficult to observe such an event due to its rareness. Paczyński (1986) first estimated realistic rates for microlensing toward crowded stellar fields, such as the Large and Small Magellanic Clouds and the Galactic Bulge (GB, Paczyński 1991), to study Galactic dark matter, Galactic structure and extrasolar planets. The first microlensing candidates were reported by the MACHO (Alcock et al. 1993), EROS (Aubourg et al. 1999) and OGLE (Udalski et al. 1993) collaborations. Following this, a few thousands of microlensing events have been detected to date, mostly towards the GB. Currently, the OGLE and MOA (Sumi et al. 2003) collaborations are detecting  $\sim 600$  events every year. All of these events have been found only in distant, dense stellar fields. This is because the rate of microlensing is very small,  $\sim 10^{-5}$  events/star/yr even toward the GB, which is the most dense stellar field in the sky. The rate for the whole sky down to  $V = 12$  mag for the source stars is estimated to be  $\sim 0.05 - 0.2$  events/yr (Nemiroff 1998, Han 2007).

Here we report the observation of the first microlensing event for a very close ( $\sim 1$  kpc), bright star as a microlensing source that is not within a dense stellar field. We present spectroscopic follow-up data, which are used to judge that this event is most likely due to microlensing rather than an intrinsically variable star. We also present observed light curves to demonstrate that the microlensing hypothesis is plausible. In §2 we detail how the event was discovered. §3 contains the spectroscopic analysis, and §4 is devoted to the photometric observations and the light curve analysis. Discussion and conclusions are given in §5.

## 2. Discovery

On 2006 October 31, an amateur astronomer A. Tago found that the star GSC 3656-1328 at (R.A., Dec., J2000.0)=(00h09m21.9948s, +54°39′43.832″), i.e.,  $(l, b)=(116.8158^\circ, -07.7092^\circ)$ , near the Cassiopeia constellation, had brightened by  $\sim 4.5$  mag. He used a commercial digital camera with 70 mm f/3.2 optics, which has a  $\sim 400$  deg<sup>2</sup> field of view. This discovery was rapidly reported to the Central Bureau for Astronomical Telegrams <sup>1</sup> (CBAT; CBET 711) and the Variable Star NETwork (VSNET; Kato et al. 2004). Following this, a special alert was announced by the American Association of Variable Star Observers <sup>2</sup> (AAVSO; ASN 22). Meanwhile, Y. Sakurai, an amateur astronomer, independently discovered the same event.

The source star is a normal A-type star with  $V=11.4$  mag at 1 kpc (CBET 711, 712). A. Tago had discovered this event during his systematic nova survey along the Galactic disk, covering  $\sim 4500$  deg<sup>2</sup> in total down to  $\sim 12$  mag, and sampling once every other night. Such surveys have been conducted for more than 30 years by many amateur astronomers, including him. The object was found by visually comparing successive images with a reference image using the eye-blinking method.

Spectroscopic and photometric follow-up observations were promptly obtained, and as the spectra contained no known signatures of variable stars, the possibility that the brightening was due to microlensing was reported to the Astronomer’s Telegram <sup>3</sup> (ATEL; ATEL 931) web site.

## 3. Spectroscopic observations

We started our spectroscopic campaign on this variable object 1 night after we received the report on CBET 711. Five sites were employed: the Okayama Astrophysical Observatory (OAO), Bisei Astronomical Observatory (BAO), Fujii Bisei Observatory (FBO), Gunma Astronomical Observatory (GAO), and Nishi-Harima Astronomical Observatory (NHAO). For the 2006 November/December period, spectra were obtained as follows: 2006 November 1 (GAO, FBO, BAO, and OAO), November 4 (FBO and OAO), November 8 (FBO and GAO), November 12 (BAO), December 2 (NHAO), and December 11 (GAO). See Table 1

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<sup>1</sup><http://cfa-www.harvard.edu/iau/cbat.html>

<sup>2</sup><http://www.aavso.org/>

<sup>3</sup><http://www.astronomersteletgram.org/?read=931>

for instrumental details.

All frames were reduced in the standard manner using IRAF, CCDOPS, and MaxIm. The latter two software packages were used for dark subtraction and flat-field averaging in the case of the FBO data. Flux calibration using a local standard star was applied to all spectra except for those obtained at OAO with the HIgh Dispersion Echelle Spectrograph (HIDES; Izumiura 1999). The typical error in the flux calibration is estimated to be 10%-20 %.

Low-dispersion spectra were obtained in the period 2006 November 1 to 2006 December 11. We continued the campaign for about 1 month after the object returned to its quiescent state in order to check for any spectral variation. All the spectra are displayed in Fig. 1. The Vega spectrum shown at the top of this figure was retrieved from the Medium resolution INT Library of Empirical Spectra (MILES <sup>4</sup>). It is clear that all these spectra have the same blue trend in the continuum, which is independent of the brightness of the object. This trend well matches that in the Vega spectrum, and the wavelengths at the peak intensities are also consistently close to that of Vega. These facts suggest that the variable object has a spectrum of a normal early A-type dwarf, both during the bright state and when in quiescence.

The high-dispersion spectra normalized to a unity continuum value are shown in Fig. 2. These two spectra were obtained on 2006 November 1 and 4, when the object was about 6.4 and 1.9 times brighter in V compared with quiescence, respectively (see Fig. 3). While the object's brightnesses were different, both spectra contain the same absorption-line features (Balmer, Mg II and Ca II K) in terms of depth, width, equivalent width, and so on. This is clearly demonstrated by the ratio of these two spectra, displayed in the bottom panel of Fig. 2. In addition, the absorption-line features are quite close to those in the Vega spectrum, and the differences of the widths and depths of these lines between the target and Vega should be attributable to the difference between the projected rotation velocities of the two objects. Note that some of the end effects resulting from the diffraction orders could not be completely eliminated during the analysis and have remained in the continuum.

In summary, our observations revealed that the optical spectrum of the variable object did not vary from when the object was  $\sim 6.4$  times brighter than its quiescent state until it returned to this state, and that the spectrum is almost the same as that of Vega. Apart from microlensing, we are not aware of another large-amplitude brightening phenomenon with a timescale of days that does not change the object's physical properties, such as the temperature and density. For example, stellar flares and nova explosions are accompanied by

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<sup>4</sup><http://www.ucm.es/info/Astrof/miles/miles.html>

strong enhancement of Balmer emission lines, and dwarf nova-type outbursts show a decay of the Balmer emission lines. The invariance of the variable’s spectral features, and the fact that they are close to Vega’s spectrum, provide firm evidence that the source object is a normal main-sequence star of late-B to early-A type, and that this brightening event was caused by gravitational microlensing.

#### 4. Photometric observations and light curve analysis

Photometric observations were made by various observers before and after the alert, using both commercial digital cameras and scientific CCDs. A. Tago, Y. Sakurai, and Y. Sugawara obtained 22, 9, and 1 JPEG images, respectively, using digital cameras (digicam data). The observation times of data posted by A. Tago on the CBAT were initially found to be wrong, but were then corrected (A. Tago 2007, private communication). R.A.K and T.K. both obtained CCD images of the variable and posted them on the AAVSO website. The former provided 3635 V-band frames, while the latter took 3472 frames without a filter. I-band (13 CCD images) and V-band (24 CCD images) were taken by the north site (Hawaii) of ASAS (Pojmański 2002) by chance as part their survey of the north sky, and not prompted by the alert.

The scientific CCD images, in the FITS format, were reduced in the standard manner, and photometry of the variable was extracted. However, the JPEG images taken by commercial digital cameras were reduced with special care because both dark and flat-field images were not available, and the flux linearity was affected by the lossy compression method used. We estimated the uncertainties due to these effects from the scatter of a standard star as follows.

First, using three colors we added all the flux in the three images to produce a single JPEG image and then converted this into a FITS formatted image. Then about 100 stars in a  $5^\circ \times 7^\circ$  area around the event star in each image were cross-referenced with stars in the Tycho-2 catalog (Høg et al. 2000) for comparison purposes. These stars were also chosen to have a similar color,  $B-V = 0.10 \pm 0.1$ , and they ranged from 6.9 to 12 mag in  $V_T$ , defined by Tycho-2. The gain uniformity of the digital cameras in this region was determined by examining sky-flat images taken by the cameras, and it was found that they were flat over the area to better than 3%. We then performed aperture photometry on these stars using IRAF, and determined the relation between the instrumental magnitudes and the  $V_T$  magnitudes by fitting a quadratic function, taking errors in both magnitudes into account. Since the IRAF errors are relative values, we renormalized these errors by a factor so that  $\chi^2/dof$  was unity. The IRAF error of the event star was also renormalized by the same factor. Finally, the

IRAF magnitudes and associated errors of the event star were converted into  $V_T$  magnitudes using these functions with their errors.

To test whether the photometric light curve was consistent with the microlensing model or not, we fitted the combined light curve with a simple point-lens and point-source model, characterized by the three parameters  $u_0$ ,  $t_0$  and  $t_E$  (Paczynski 1986), where  $u_0$  is the minimum impact parameter corresponding to the source-lens angular separation in units of the angular Einstein radius  $\theta_E$ ,  $t_0$  is the time of maximum magnification, and  $t_E$  is the event timescale, defined as  $\theta_E/\mu$  where  $\mu$  is the relative proper motion between the source and lens stars. The baseline flux of the source star and any blended flux in each data set were also allowed to be free parameters in the fitting procedure.

In Table 2 we list the resultant parameters and the errors that were obtained for the different data subsets by checking the systematics within each one. The uncertainties in the ASAS and AAVSO data were estimated to be equal to the rms of their baseline values. These were determined using only those observations separated by an interval of at least  $3t_E$  from the peak magnification, where the amplitudes are expected to be sufficiently low. The value for  $t_E$  was determined from the fitting parameters of the digicam data set. The  $\chi^2/dof$  in each data set is close to unity except for the AAVSO data. We found that the AAVSO points were scattered about the fitted curve significantly more than expected from the estimated errors, with a timescale of  $< 1$  day. This is because the reduction and calibration of the data sets were not optimal (e.g. no air mass corrections were made), and the errors were also underestimated for some reason. Other than this, one can see that the microlensing model provides a satisfactory fit to all the data sets except for some digicam data points near the peak (refer to Fig.3). We suspect this deviation is due to the systematic errors from lossy compression, and we think this has an insignificant effect on the conclusion of this paper. Consequently, we renormalized the errors of the R.A.K and T.K. data sets so that  $\chi^2/dof$  in each one was unity, where the fitted model values were determined using all data sets, including the unnormalized AAVSO data (see "\*" in Table 2). The blended flux parameter for each data subset is nearly negligible in comparison with the source flux, except for the ASAS data set. In this case there were contributions from an unresolved neighboring star due to the low resolution.

Fig. 3 shows the complete photometric light curve, including the renormalized AAVSO data, and the best fit model to all the data. As shown in Table 2, the differences in parameters for the various data subsets are relatively small, e.g.,  $\sim 3$  days in  $t_E$  at most, which is roughly the size of the statistical errors. Therefore we conclude that systematic biases in all data sets are negligible, and the aggregate light curve can be represented well by a point-lens and point-source microlensing model.

## 5. Discussion & Conclusion

We have reported the observation of the first microlensing event in a sparse stellar field, involving the brightest ( $V=11.4$  mag) and closest (1 kpc) source star to date. The spectra of the source star and the overall light curve show that this event cannot have been caused by any known mechanism for intrinsically variable stars, but it can be naturally explained as a microlensing event.

Gaudi et al. (2007) also reported the discovery of the same event, and also concluded that this event is most likely due to microlensing. A subset of the data used in this paper is in common with theirs, but our analysis was carried out independently, and we have original data taken by amateur astronomers, which includes coverage of the peak magnification region.

The rate for the microlensing event described here is estimated to be very small at  $\sim 0.05 - 0.2$  events/yr over the whole sky (Nemiroff 1998, Han 2007), so it seems reasonable for one such event to happen in a 30 year period. However, this event is a high amplification one, so the corresponding rate is much smaller ( $\sim 1/50$ ) than that given above. This may be just good luck, or the true event rate may be higher than expected but low-amplitude events may be missed by the current nova surveys with digital cameras, where the detection efficiency is uncertain. Such a possibility can be addressed by systematic all-sky surveys featuring frequent sampling with small apertures and wide fields of view, such as LOTIS (Park et al. 2002), ROTSE (Woźniak et al. 2004) and ASAS (Pojmański 2002). We can expect to detect some microlensing events/yr for all-sky surveys down to  $V = 15$  mag (Nemiroff 1998, Han 2007).

Searching for exo-planets (Mao & Paczyński 1991) in very bright microlensing events is also a worthwhile exercise. Although the expected number of these events is small, e.g. 1 planet every 4 years if assuming 5 microlensing events observed each year by an all-sky survey and 5% planet abundance, the detection efficiency for planets in such bright events is much higher than for faint events, because the photometric precision of a bright event is higher (Peale 2001). In addition, such high precision can be achieved even by small-aperture telescopes distributed around the world. Even if we can detect only one planet in such an all-sky survey in 2-10 years, it will be the first planet discovered by microlensing in the solar neighborhood which can be confirmed by other methods such as spectroscopy or direct imaging after the peak amplification phase has ended. This will be very important to convince people that the planetary signal in the microlensing that we are also seeing towards the bulge is actually caused by the planet.

This discovery shows the potential of all-sky variability surveys using cheap, small tele-

scopes for finding rare transient events, which in turn will provide information on disk structure and possible exoplanets.

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Table 1. Telescopes and instruments used for spectroscopic observations.

Site <sup>a</sup>	Tel.	Instruments	WR <sup>b</sup> (Å)
OA0	188cm	HIDES <sup>c</sup>	0.07
BA0	101cm	Low Dispersion Spectrograph	5
FBO	28cm	Low Dispersion Spectrograph	10
GA0	150cm	Low Dispersion Spectrograph	13-14
NHA0	200cm	MALLS <sup>d</sup>	6

Note. — <sup>a</sup> OA0: Okayama Astrophysical Observatory, BA0: Bisei Astronomical Observatory, FBO: Fujii Bisei Observatory, GA0: Gunma Astronomical Observatory, NHA0: Nishi-Harima Astronomical Observaotry, <sup>b</sup> WR: Wavelength resolution, <sup>c</sup> HIDES: HIgh Dispersion Echelle Spectrograph (Izumiura 1999), <sup>d</sup> MALLS: Medium And Low-dispersion Long slit Spectrograph

Table 2. Lensing fit parameters.

dataset	$t_0(HJD - 2450000)$	$u_0$	$t_E(day)$	$N$	$\chi^2/dof$
digicam	4039.93 (0.02)	0.0197 (0.0134)	4.70 (2.87)	32	1.04
ASAS	4039.99 (0.13)	0.0221 (0.0129)	6.20 (0.95)	37	1.08
AAVSO	4039.87 (0.006)	0.0184 (0.0029)	6.98 (0.02)	7107	6.75
AAVSO*	4039.98 (0.02)	0.0367 (0.0038)	7.74 (0.10)	7107	0.97
ASAS+AAVSO*	4039.92 (0.005)	0.0229 (0.0014)	7.53 (0.05)	7144	0.98
digicam+AAVSO*	4039.89 (0.004)	0.0107 (0.0018)	7.48 (0.004)	7139	0.98
digicam+ASAS	4039.98 (0.01)	0.0148 (0.0020)	7.24 (0.66)	69	1.27
digicam+ASAS+AAVSO	4039.88 (0.002)	0.0199 (0.0010)	6.99 (0.02)	7176	6.71
digicam+ASAS+AAVSO*	4039.91 (0.003)	0.0189 (0.0011)	7.53 (0.04)	7176	0.99

Note. — digicam: Data from digital cameras. ASAS: ASAS I and V band. AAVSO: CCD data from R.A.K. and T.K. \*: Errors in R.A.K. and T.K. data sets are rescaled independently by multiplying the factors so that  $\chi^2/dof$  in each data set was unity, calculated from a model fitted by using all data sets including the unnormalized AAVSO data. The numbers in parentheses represent 1- $\sigma$  statistical errors which corresponding to the values where  $\Delta\chi^2$  is 1.

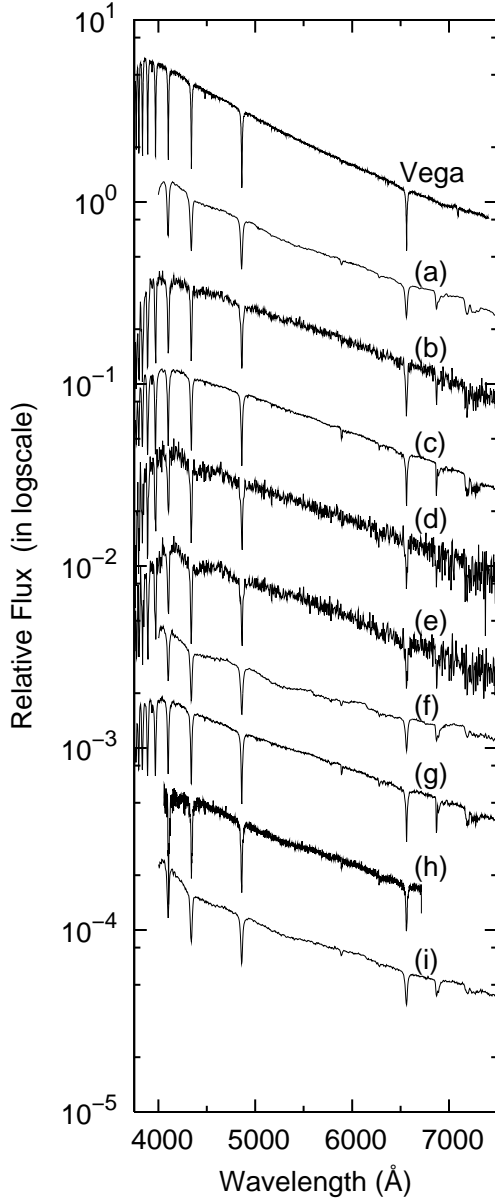


Fig. 1.— Low-dispersion spectra obtained between 2006 November 1, and 2006 December 11, and a spectrum of Vega (A0V). The vertical axis is the relative flux using a logscale. The spectra have been arbitrarily scaled in the vertical direction for visual purposes. The Vega spectrum was retrieved from the Medium resolution INT Library of Empirical Spectra (MILES). (a), (f) and (i) were obtained at GAO. (b), (d) and (e) were taken at FBO. (c) and (g) were taken at BAO and (h) was at NHAO. The blue trend of the continuum did not change within the error of the flux calibration, and is in good agreement with that of the Vega spectrum.

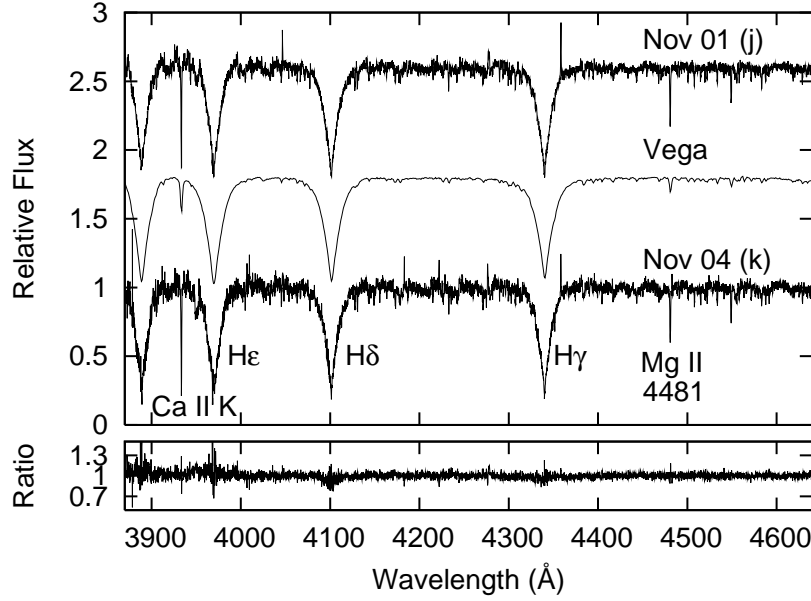


Fig. 2.— High-dispersion spectra of the event star obtained on 2006 November 1 and 4 at the OAO. We have also included a spectrum of Vega for comparison purposes: it was obtained at Steward Observatory using a 90 inch(2.3m) telescope, and is publicly available on the Web (<http://stellar.phys.appstate.edu/stdSO90.html>). These spectra have been normalized to a unity continuum value and arbitrary shifted in the y axis direction for visual purposes. The absorption features of  $H\gamma$ ,  $\delta$ , and  $H\epsilon$ , Mg II and Ca II K did not change between the observations and are very close to those of Vega. The bottom panel shows the ratio of these two spectra ((j)/(k)).

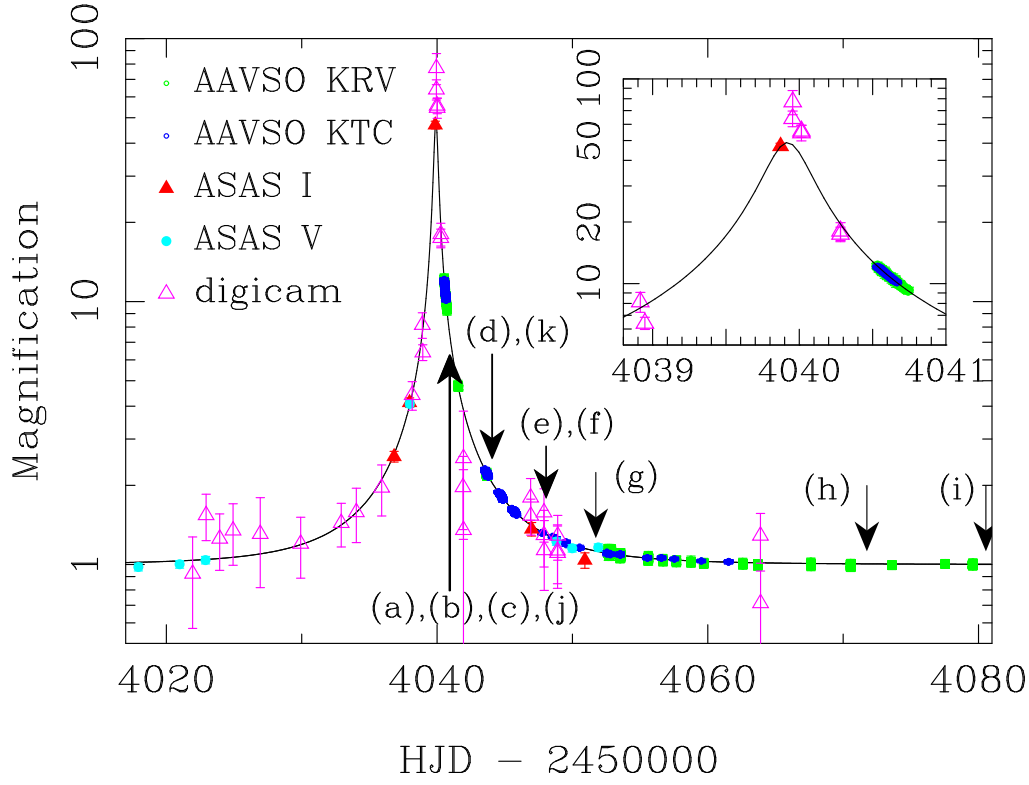


Fig. 3.— The light curve of the Tago event. The solid line indicates the best fit point-lens and point-source model. Errors in the AAVSO data have been re-normalized as noted in the text. The arrows (a) - (k) indicate the epochs of the spectroscopic measurements depicted in Fig 1 and Fig 2.